

Final Report

Title: Micro Hopping Robots for Rescue Operation
-3rd Report: - Location of the distributed many tiny robots under the collapsed building -

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1.Introduction

<Background>

Collapsed buildings due to earthquake or terrorist attack typically result in a rubble pile with access holes less than 1 foot in diameter. The necessity of producing smaller robots which can locate survivors quickly is evident in light of recent disasters and attacks. In the reported research, instead of developing one or two expensive robots, the proposed concept is to manufacture thousands of less expensive micro robots ($< \$10/\text{micro robot}$) which can access small openings in the rubble pile. Therefore, the probability of locating survivors increases exponentially due to the exponential increase in the number of robots and because these smaller micro robots can move through small openings which larger robots are not be able to access. Key to the approach is to place the micro robots at the top of the rubble heap so that little energy is consumed as the micro robots search downward (carried by gravity) when not utilizing their own power source.

In this project, many small hopping robots which have a simple locomotion mechanism and sensory elements have been developed to detect survivors under collapsed buildings. This small robot includes micro eccentric motors for generating lift and thrust forces, and the sensors for detecting the thermal signal of survivors. Therefore, the micro robot can crawl without any wheels or legs even on small, rough terrain with the help of eccentric mechanical vibration. This tiny robot also has the ability of self-righting to allow it to keep moving to the target even if it falls and lands in any position. Weight balance as well as resonance parameters are very important to achieve good mobility. Automatic navigation to the target is achieved with simple on-off motor switching. The simple design layout results in not only lightweight robots but also low cost allowing employment of a large number of robots in the dangerous rubble field.

Initially, a small robot utilizing off-the-shelf components (i.e. micro motors, button batteries, sensors and electronics) was designed and assembled to verify feasibility for rescue operations. In the initial experiments, many small robots with optical and IR sensors have been developed and movement toward a human body under dark conditions has been successfully demonstrated. The aim of this project is to design and to development of micro robots system to find out the survivors rapidly under the rubbles as shown in Fig.1. There are many small robots can walk into the complex and search the alive survivors autonomously, then provide the appropriate signal to identify the location.

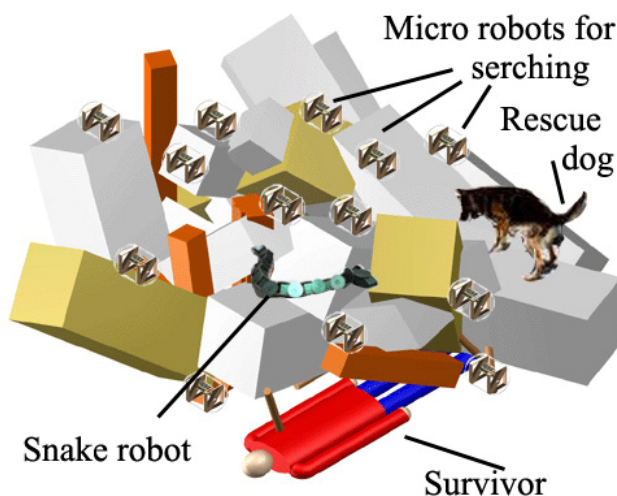


Fig.1 Rescue operation at disaster location with collaboration the dogs, the rescue robots as well as many micro robots

In the primary report, the micro hopping robots which have a simple locomotion mechanism and sensory elements have been developed to dispatch into the craves of rubble to detect the alive human. This small robot consists of micro eccentric motor for hopping and thrusting with the help of resonating vibration, as well as micro sensory element, button battery and electronics for detecting the signal source. Moreover as an unique performance, this tiny robot has the ability of the self-righting to keep moving to the target even if it drops from the step. The principle of this locomotion is based on the vibration excited by micro motor so that it can keep moving on the non-finished surface such as floor and small rough terrain.

In this report, many small robots with thermal micro sensors and micro CCD camera are designed and developed and it is demonstrated that they can move toward to the human body based on the thermal signal and transmit the visual information to the operator to check the target. And then the sound signal can be generated from the small robot. Several microphones with high sensitivity and directionality can identify the location of the coordinate position of the small robots that are close to the survivors. The aim of this project is the design and the developement of less than 1 cubic inch size robot which can be composed of the off-the-shelf components. This strategy can give us the benefit of reduction of cost, large-scale employment as well as disposable use. By large-scale employment of many tiny robots a widespread search and rescue operation can occur over the disaster field at minimal risk to rescuers and maximizing probability of survivor location and rescue.

<Previous works from May 2002 to Sep 2005>

In the previous work, we succesfully developed the prototypes based on hopping locomotion manner. To check the basic performances such as mobility and durability, the prototype (I) in Fig.2 was designed and constructed by using many off-the-shelf componets. Then it was confirmed that this simple mechanism could move at the speed of 65mm/sec. And it was verified experimentally that this small hopping locomotion mechanism had the durability of 350 minutes with the battery of LR44, 100 minutes with CR1616 button battery.

Alternative style in which the sensory device and some electronics as well as the wire frame guard was implemented was also designed and developed to check the automatic navigation to the target and the self-righting performance as shown in Fig.3.



Fig.2 Original tiny hopping robot with resonated cantilever mechanism

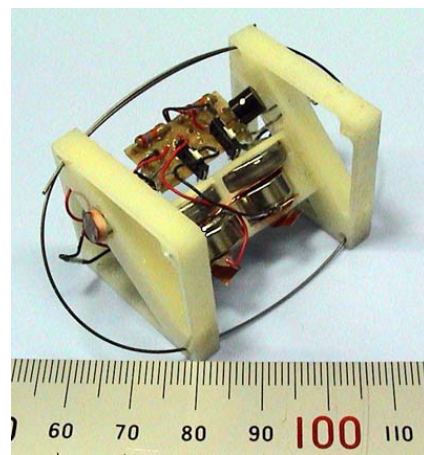


Fig.3 Small hopping robot with twin micro flat motors and wire guard frame for self-righting

Two small eccentric motors were incorporated at the center of the body and this layout allowed the small body to take the turn to the left and right when one of each was activated, although the elastic resonator was not built in yet. Many small robots were fabricated to check the robustness and the auto-navigation as shown in Fig.4.



Fig.4 Fabricated many small robots with sensor to detect the human target and navigate itself.

In the primary experiment, this micro robot with the piroelectric IR sensors as shown in Fig.5, succeeded in tracking the thermo signal of human body as the target in the dark after as shown in Fig.6. And the micro camera also has been implemented into the small robot to check the visual image around the robot as shown in Fig.7. The small robot with these devices can approach to the human body and transmit the visual image to the operator to check the target condition.

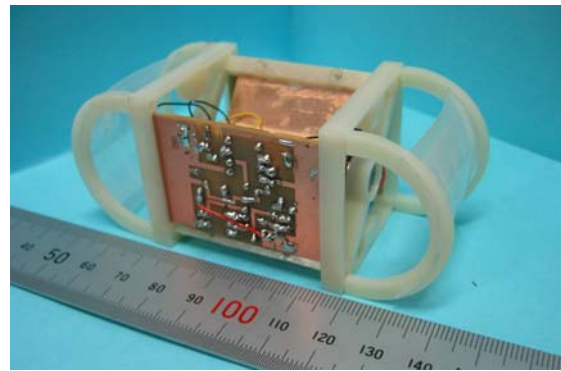
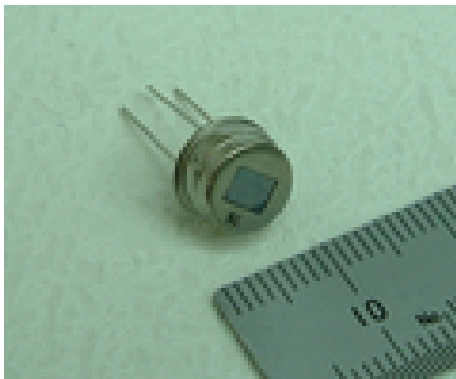


Fig.5 Piroelectric IR sensors to detect the thermal signal from human body and small robot with these sensors to track the target automatically

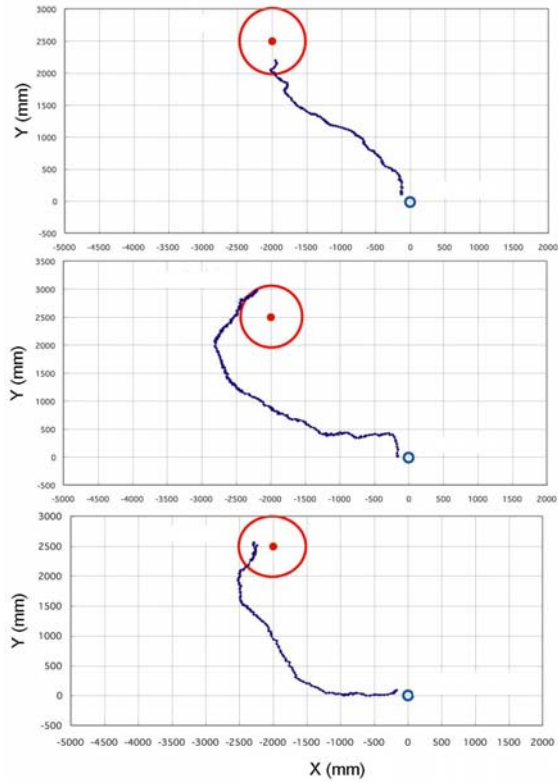


Fig.6 Experimental result shows that the small robot with IR sensor succeeded in tracking to the human body in the range of 2.5 m

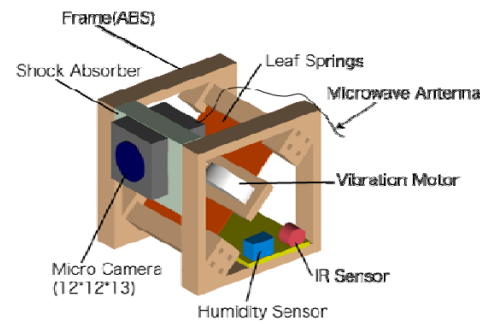
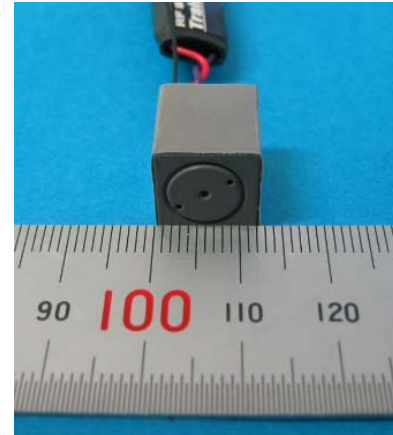


Fig.7 Micro CCD camera(RF System Inc. Japan Model RC-12) also will be implemented on the small robot to get such visual information of the situation and transmit it to the operators

<New proposals in this report>

In order to find out the survivors under the rubbles, the location of the distributed micro robots that can arrive at them is significant issue as well as the identification of human signal. In this proposal, the acoustic signal based location system to find out the many small robots are to be developed at first and the stand-by signal from the cellular phone with the survivors also can be one of the techniques to verify the final location.

There are some technical issues and challenges as mentioned below to be considered.

- (1) Sound signal generator capable of being implemented into the tiny robots with CCD camera.
- (2) High directional multiple microphones can be controlled to scan the field to detect the signal sources. After some signal processing, the locations of many small robots can be estimated
- (3) Small robots also can be launched to the field over the obstacles by the launcher mechanism the sound signal from the robots can be detected by the microphone array to decide the direction and the distance in order to identify the location of each robot in the field.
- (4) Combination of local coordination data and global one can provide the location map of the distributed small robots to find out the target.

<Project schedule with milestones>

Proposed Duration: 24 months;

September/2006. Project Start

- Implementation of acoustic generator and simple logic electronics into the small robot
- Measurement of the signal propagation even in the rubbles

January /2007

- Experiment to check the location of the micro acoustic source by using many high sensitive directional microphones
- Examine the microphone scanning performance to direct the signal source for the signal processing by the PC

August/2007

- Interim Project Report

December/2007

- Field experiments that many small robots with the signal generator can be distributed around the rubbles by using the launcher and check the error of measurements.
- To check the location relay technique, the detected data from each robot can be processed within the local near field

February/2008

- Overall experiment that small robots with IR sensor can be distributed over the rubbles and they can approach to the human survivors. When they can arrive at the target, the special acoustic signal can be propagated to identify the each location

August/2008

- Delivery Document of Technical Final Report

2. Improved tiny hopping robot

2.1 Background

In our previous works, several small hopping robots with such optical and IR sensors have been developed[1] [2] . However, they have still many problems to apply them into the actual situation because the lack of mobility of small robots causes that they can be stuck before the obstacles. Thus, it is required to make the assisting system to help such many small robots with human detectors. Here there are several plans to be considered to develop the assisting mechanism, (1) Easy transportation and maintenance as well as low cost to employ them, (2) Convey many small robots near to the front end of the dangerous location the mother-ship vehicle and launch them to deliver them over the obstacle under the visually remote-control by the operator. After that, it can be possible to use many small robots with detectors for a useful rescue work when large scale disaster that needs wide field of search and a lot of numbers of searchers.

2.2 Thermal sensor and micro CCD camera

Small vibration coin motor (FM34F, Fuji Motor Co. Japan) was used as an actuator in the small locomotion mechanism. Locomotion principle of robot that uses this motor is discussed in the previous report. This locomotion mechanism is driven by the unbalanced force generated by cyclic force of the vibration motor. Alternative force can thrust up and forward the body, while the reversed force can push it down on the floor. So, the vibration motors are fixed at certain angles with ground. With this layout, the body can be driven to the one direction based on the differential force of the friction and the centrifugal force. In order to allow the micro robot to turn, a pair of micro motors are included and the current to each motors can be alternated. Then either of two motors provides the momentum force required to turn the micro robot. Two of these motors are built onto the micro robot as shown in Fig.8.

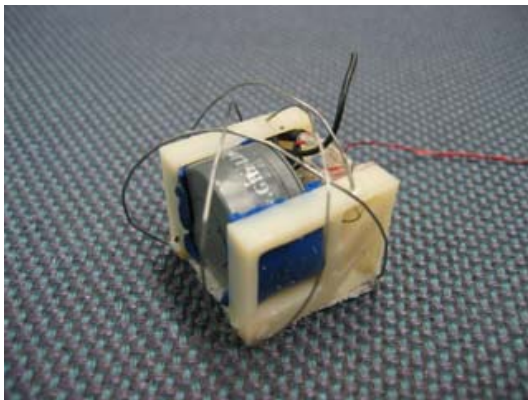


Fig.8 Micro hopping robot with CCD camera and twin coin motors.

Current is supplied by the wire

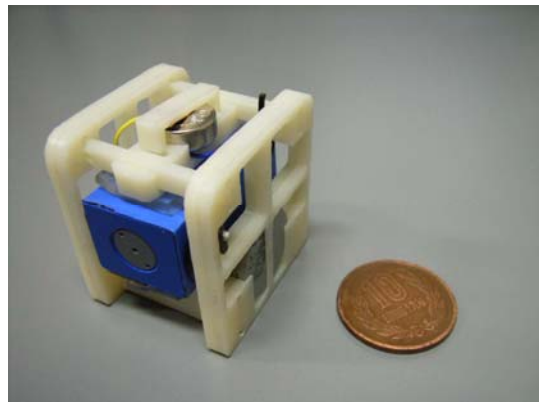


Fig.9 Advanced prototype of micro hopping robot with CCD camera, twin coin motors, electronics and battery. The image can be transmitted to the remote monitor.

In the previous works, optical sensor and IR sensor were mounted on the micro robot to allow to approach the illuminant and thermal source like a human. However, there was the problem that the thermal source could not be distinguished between human and another thermal source in actual disaster area. In this small robot, a small CCD camera(RF Co. Ltd. Japan, Model ME) is implemented on the small robot and the visual image can be transmitted to the operator although the electric power is still supplied by the cables. However the real image from the camera is displayed on the screen and then the micro robot can be navigated to the point to check out the situation. Control of the robot can be done to use a simple jog controller that switches the current to each motor and the motion direction can be easily changed. The typical speed of 50 to 60 mm/s can be achieved on the smooth flat surface while it is still not enough to employ them in the practical applications. Advanced version as shown in Fig.9 is fully self-contained version that the smaller CCD camera(RF System Inc. Model RC-12) , motors, electronics and battery are included on the body. Typical durability of this type is approximately 30 minutes and we need much more higher performance battery with low power consumption devices.

It is also important issue to improve the mobility of these small hopping robot. Thus several new mechanisms have been considered for these years. One of them is that the small robot has the fiber brush legs underneath in order to enhance the vibration as shown in Fig.10. Thanks to inclined brush fibers, the thrusting force of vibration motor can be enhanced and thus the moving speed can be improved because the elastic force of inclined brush contributes to increase the speed of robot. In the experiment, it was confirmed that the maximum speed of 200mm/s was achieved when the fiber inclined angle was set at 20 degree. In the actual small robots, several sensors such IR thermal and piezoelectric detectors(Matsushita. NaPion Type AMN241111) and have been implemented as shown in Fig.10 to check thermal signal from the human body as well. Two sensors is implemented to both side for automatic navigation of the robot as shown in Fig.11. The simple sequence that the detected signal from the thermal source can directly switch the current to the motor in Fig.12 is designed and then it can turn the heading to the target with such reflective action although PIC is used for the PWM current control with the advanced version.

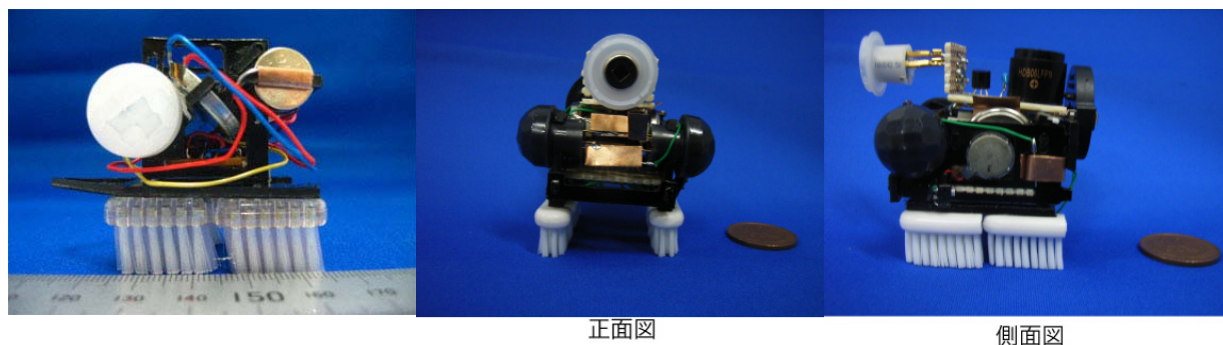


Fig.10 Improved prototype of micro hopping robot with fiber brush underneath, IR sensor, twin coin motors, buzzer,electronics and battery.
When it can arrive around the target, then it can generate the sound signal.

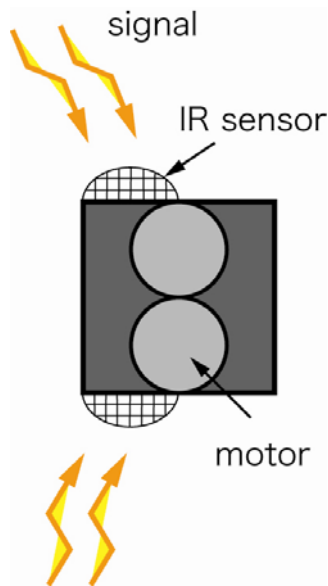


Fig.11 Layout of the IR sensors and two coin vibration motors. The received current can switch the current to each of the motor

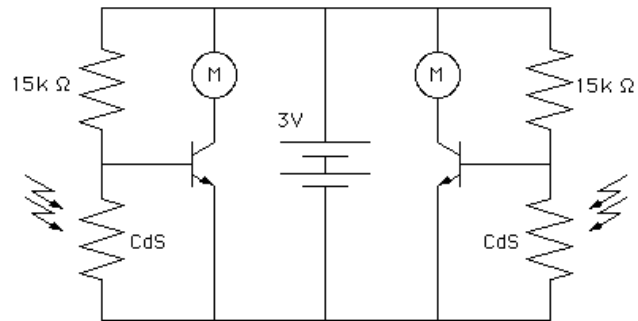


Fig.12 Simple electronics can alternate the current to the motor so that it can change the heading to the target.

One detector is set to the head of robot for checking the temperature of the target. To measure the range of temperature from the target is very important to identify that it is human or another thermal source such fire. In the experiment, more than ten small robots with several sensors were assembled for distributing them around the field and to check its performance as shown in Fig.13. Here many small robots with the different function with each small robots can allow them to work individually at first. When one of them can find the target, then the appropriate signal will be generated to inform the location. In the primary experiment, the simple buzzer is also implemented to each small robot and it can provide the acoustic signal when it can arrive around the target and the locations of them can be identified by the multiple microphone array.

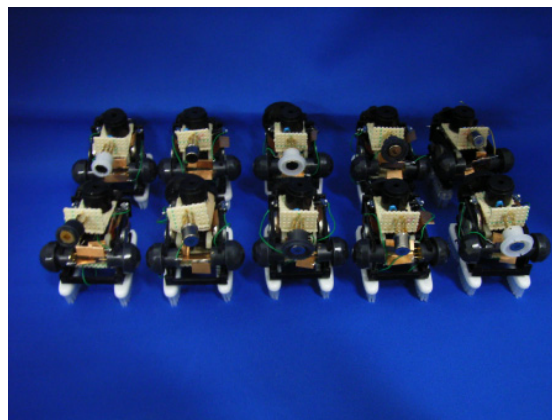


Fig.13 More that 10 small robots have been fabricated for the experiment

2.3 Basic performances

In the previous report, the typical mobility of the tiny hopping robot was discussed. Here the basic target tracking performances are discussed. In Fig.14, the simple tracking control sequence is shown by the sequential pictures. The small robots can not detect any signal, then they can keep going to the random direction. When the thermal signal can be detected by the sensor, then the current to the vibration motor in the same side is cut off and then the small robot can change its head to the target. At the first stage, in order to avoid the complicated circuit, the detected signal can directly control the transistor gate current to each motor. However it causes on-off action with the small robot and the moving speed became so slow. To this problem, PIC is implemented to control the PWM current driving the motors according to the amounts of the received signal. Then the small robot can move and turn smoothly to the target.

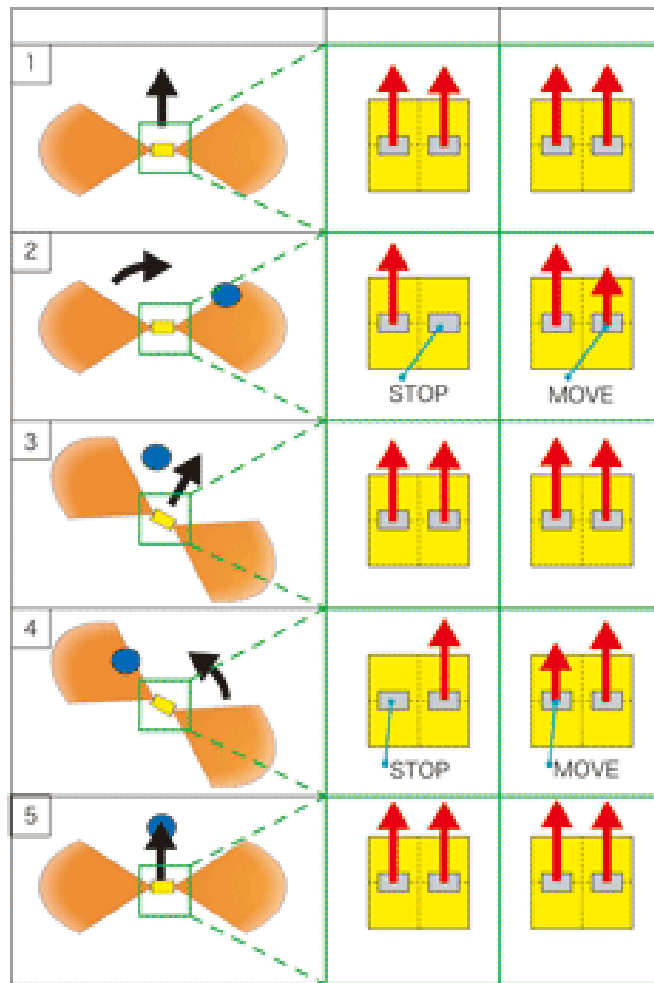


Fig.14 Sensor based reflective simple navigation with on board PIC controller of PWM current switching to each motor for heading to the signal source.

In Fig.15(a)-(d), the sequential photo of the experiment is shown. Here the small robot succeeded in detecting the thermal signal from the target human and then control the direction to approach the target automatically. The relation between the arrival time and the distance to target were checked in Fig.16. When the target is within the range of 2 or 3 m, it can arrive at the target within approximately three minutes with 100%, while the target is 10m far from the robot, then it takes approximately 30 minutes and the successful ratio is less than 30%. In the practical application, many small robots can be distributed over the field, so the possibility that one of them can find the target should be more higher.



(a) Small robot starts at the initial point



(b) It can head to the thermal signal source



(c) It approaches to the human



(d) It can arrive at the goal.

Fig.15 Sequential photo shows that the small robot can move to the thermal signal source of human with the simple navigation manner

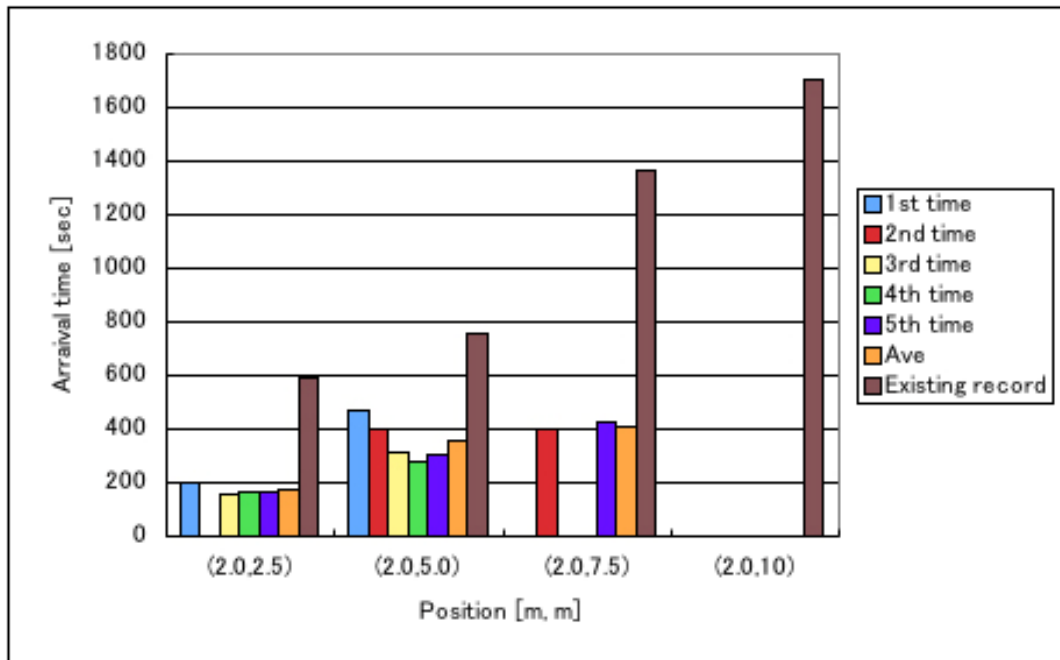


Fig.16 Rate of the target tracking with the distance of 3m, 7m and 10m

3. Launching mechanism

3.1 Background

It is most important for such small robots to move over the rubbles in the terrible field although they still have the limited mobility to climb up or jump up themselves. Here we are proposing the launching mechanism for many small robots to move over the obstacles. It's also possible to reduce the operation time to search of survivors by using this device. As illustrated in Fig.17, such small robots can be launched from the mother-ship to move over the big rubbles. And then the small robot can land on the floor and start to search the target.

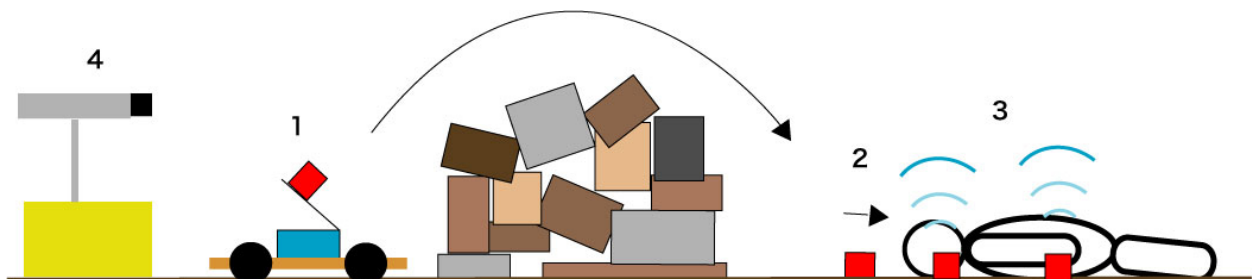


Fig.17 Illustration of the combination with the launching mechanism and small robots with sensor to find out the survivors over the rubbles.

3.2 Catapult-assisted launch mechanism

Several devices can be considered for the launching mechanism from the view points of such (1)A blast by the gun powder, (2) Acceleration by electromagnetic force, (3) Elastic energy of rubber and spring etc. In terms of thrusting force, (1) and (2) should be appropriate to employ for the launching devices, however these mechanisms become more complicated and small force can be enough to push up the small robot as the mass of that is approximately the weight of several ten grams. Other most important issue is that the launching mechanism can never provide such spark or fire, because it is expected that some gas can be leaked around the launching mechanism and be exploded in the practical situation. Hence a simple mechanism can be better for the point of maintenance and cost. In this experiment, the actuator of the rubber and the spring can be used for our launcher. To gain energy enough to launch the small robot, it is necessary to extend the rubber or spring. Catapult-assisted launch mechanism with the leaf spring is designed and fabricated as shown in Fig.18

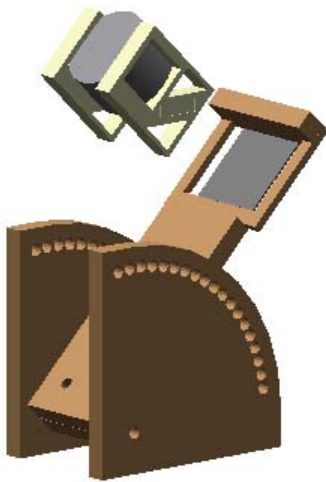


Fig.18 Simple leaf spring catapult launching mechanism to push out the small robot with no spark and no explosion



Fig.19 Spring can be bended by the wire and it can be cut off with thermal melt-down device for ejecting

3.3 Mechanical Structure

Each part of this catapult-assisted launch mechanism is discussed here.

(1) Adjustment of the leaf spring of the catapult mechanism

In order to launch the small robot to take over the rubbles, the injecting force and the launching angle are dominant to determine the distance for arrival and the top height of jumping. These conditions depend on the situation and then the range of launcher should be adjustable with the control of preset. Thus the expansion of the leaf spring and the catapult angle of launching lever are designed and fabricated to be adjustable with several steps of preset. In this mechanism, we can preset both the leaf spring expansion and the angle of ejection as mentioned below. The expansion amount of the leaf spring in the launcher can be read out with the wire winding drum and it can be estimated the force of ejection as shown in Fig.19 . As shown in Fig.18, the angle

of catapult can be adjusted with the pit stopper which is preset and thus the top height can be estimated by using the simple motion equation. The small robot can be set into the holder that is fixed at the end of the leaf spring to prevent from unexpected slipping and falling down.

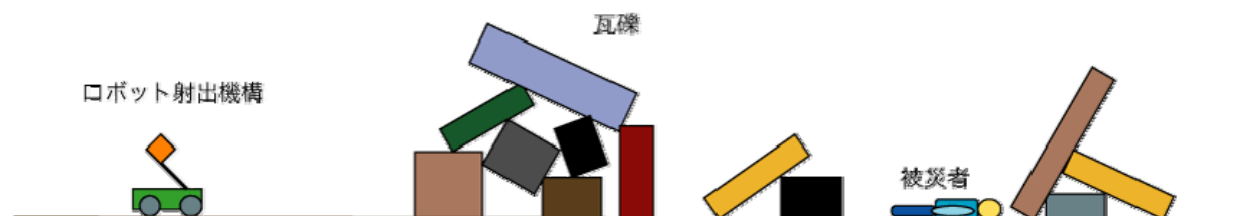
(2) Melt-down wire cut for ejection

It is well known that one of reason that robots are used to rescue work in disaster area is the replacement of human operation even in such dangerous situation. Thus it is necessary to operate the catapult-assisted launch mechanism by remotely control manner. In the proposed mechanism, the leaf spring can be bended by the wire that is winded up the drum in order to keep the energy enough to eject the small robot. In order to cut off the wire, the thermal heater is set close the wire and the current causes the wire to be melt down as shown in Fig.19. Then the small object can be push away from the catapult. This simple and classic manner is enough to operate with the good reliability.

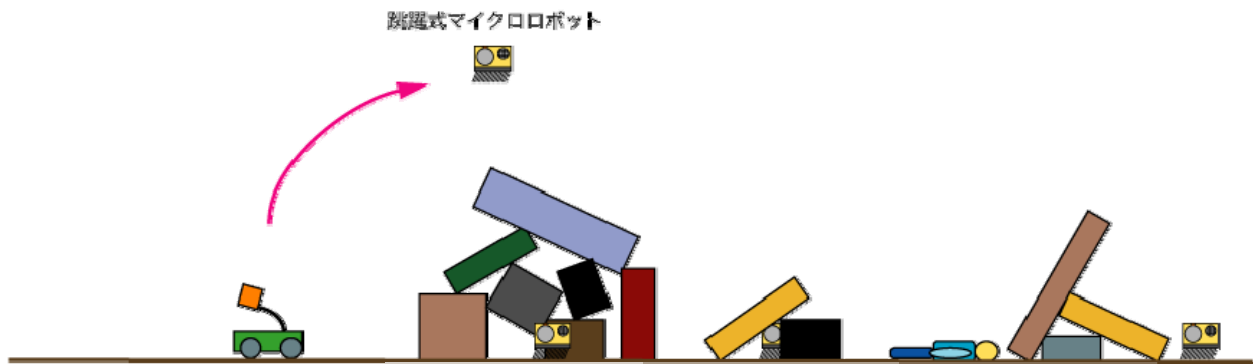
3.4 Basic Performances

As the the scenario is shown in Fig.20, the mother-ship with the launching mechanism can apporach around the big rubbles(Fig20-1). Then several small micro robots with IR or thermal sensors can be pushed away over the obstacles(Fig.20-2). When some of them can find out and approach the survivors, then they can provide the sound signal(Fig.20-3) . The second small robot with micro CCD camera can be launched to the sound signal source and then the target image can be transmitted and monitored by the operator.(Fig.20-4)

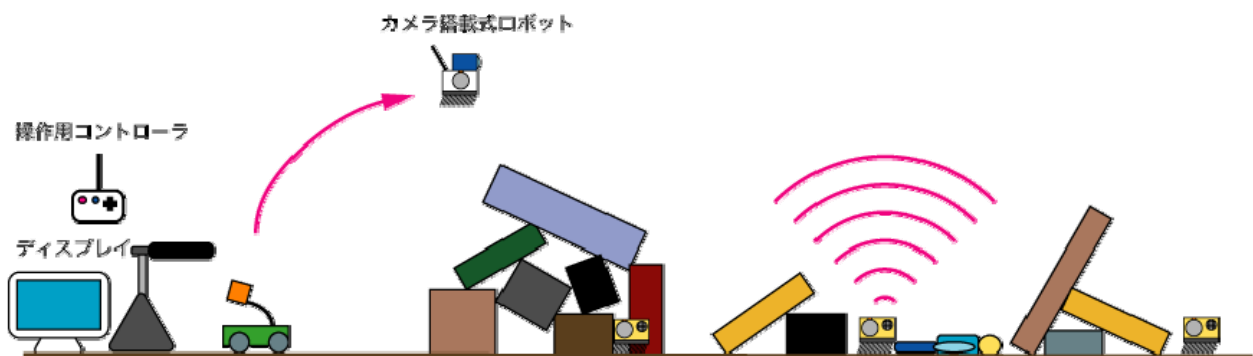
In order to check the range of the launching mechanism, we carried out the experiment with the manner as shown in Fig.21. Here the arraval distance and highest attitude were measured by using the high spped camera. As the result of these experiences in Fig.22, this sipmple launching mechanism with the leaf spring can convey the small robot over 4m away and push it up to 1.5 m in height.



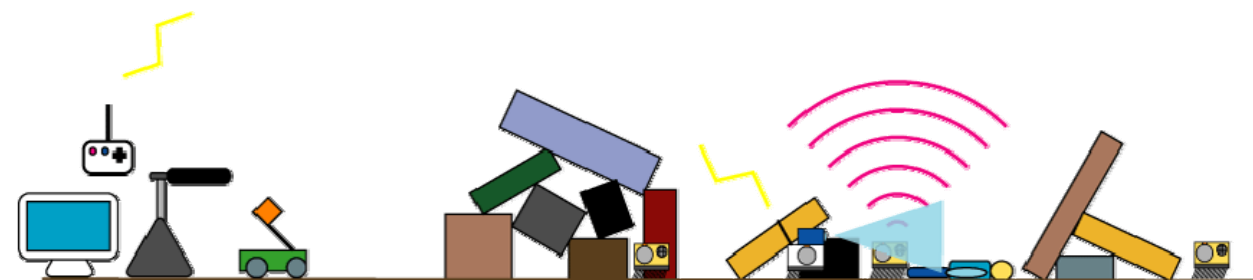
(1) Mother-ship with the launching mechanism can apporach around the big rubbles



(2) Several small micro robots with IR or thermal sensors can be pushed away over the obstacles



(3) Some of them can find out and approach the survivors, then they can provide the sound signal



(4) The second small robot with micro CCD camera can be launched to the sound signal source and then the target image can be transmitted and monitored by the operator.

Fig.20 Illustration of the combination with a mother-ship launching vehicle and micro robots with sensor and CCD camera

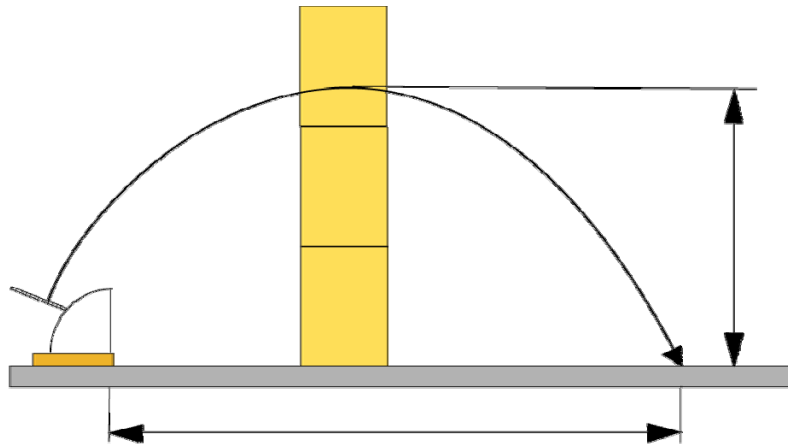
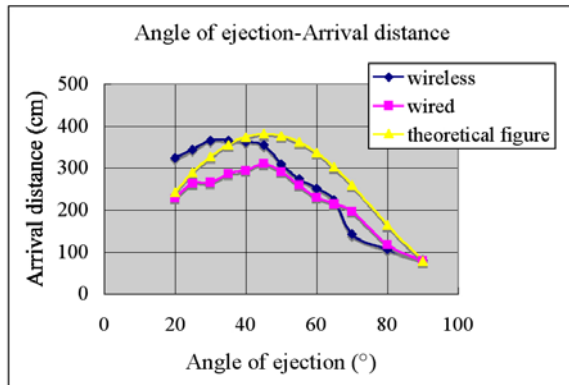
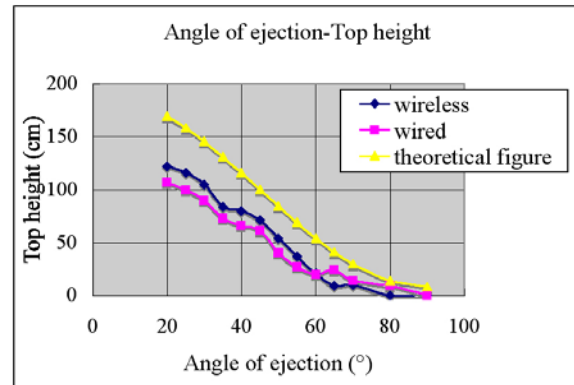


Fig.21 Simple experiment to check the performance of the launcher with the arrival distance and highest attitude.



(a) Arrival distance and ejection angle



(b) Achievable attitude and ejection angle

Fig.22 Simple experiment to check the performance of the launcher with the arrival distance and highest attitude.

4. Location measurement based on sound propagation

4.1 Measurement of the sound signal from distributed small robots

In order to find out the survivors under the rubble, the location of the distributed micro robots that can arrive at them is a significant issue as well as the identification of human signal. In this section, the acoustic signal based location system to find out such many small robots are developed at first and the stand-by signal from the cellular phone with the survivors also can be one of the techniques to verify the final location.

There are some technical issues and challenges as mentioned below to be considered.

- (1) Sound signal generator capable of being implemented into the tiny robots with CCD camera.
- (2) High directional multiple microphones array can be controlled to scan the field to detect the signal sources. After some real time signal processing, the locations of many small robots can be estimated in the field.
- (3) Small robots also can be launched to the field over the obstacles by the launcher mechanism the sound signal from the robots can be detected by the microphone array to decide the direction and the distance in order to identify the location of each robot in the field.
- (4) Combination of local coordination data and global one can provide the location map of the distributed small robots to find out the target.

4.2 Measurement principle and experimental set up

Two microphones with parallel layout can detect such the amount of the differential time between them and the direction of the sound signal source can be calculated as shown in Fig.23.

As shown in Fig.24, here the actual phase delay with the received waveforms can be analyzed by the processor and then the direction can be estimated although there are several disturbances such as the reflected waveforms.

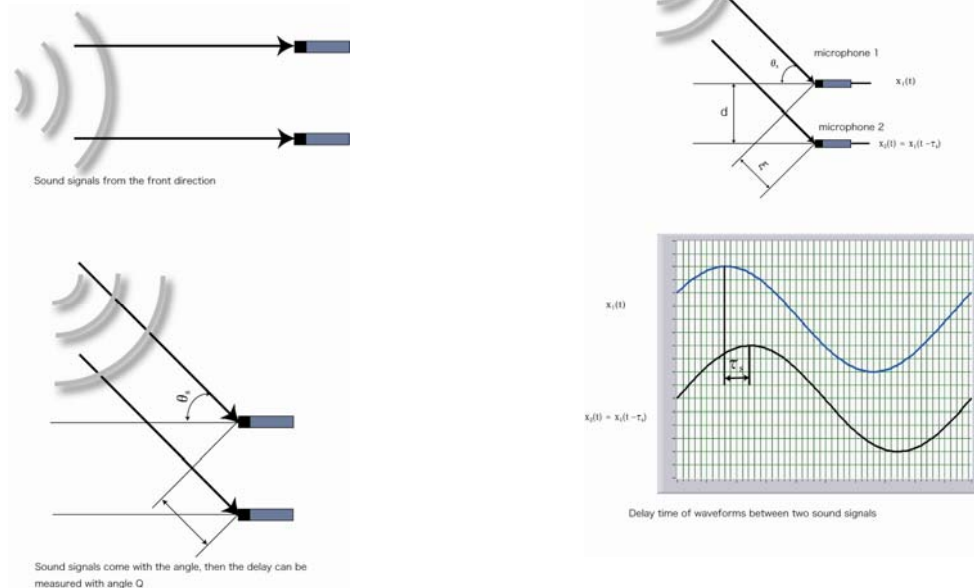


Fig.23 Simple measurement based on the time delayed sound signals with two microphones.

Fig.24 The phase difference between two detected waveform can be monitored and processed to determine the signal source direction

In order to locate the sound signal source, the distance and the direction can be measured by the simple trangulation manner as shown in Fig.25. However it is expected that there are many reflected wave signals from the walls or the obstacles. Thus the special numerical data processing is implemented to filter such unexpected noises and to get the well collirated signal from the source.

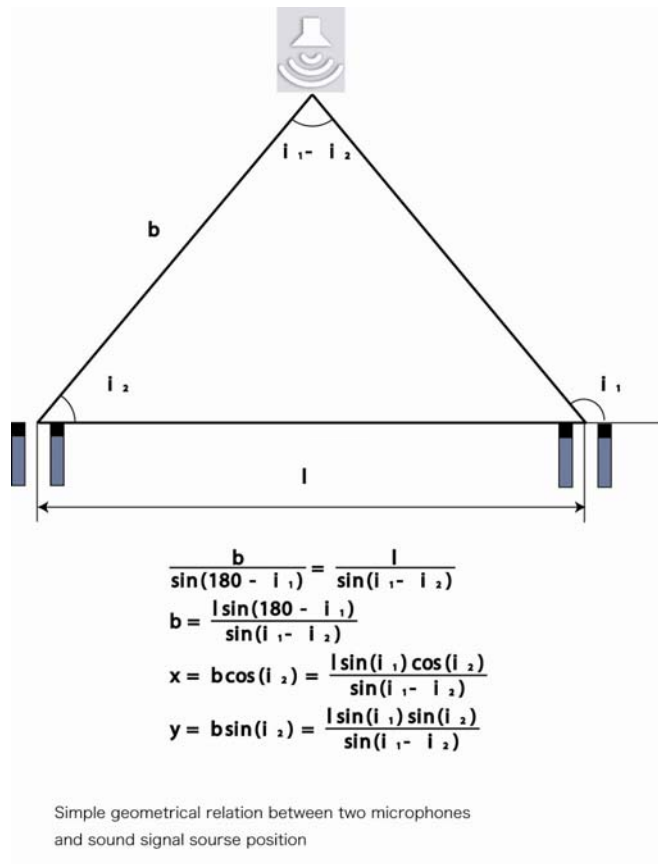


Fig.25 Typical layout of twin microphones to determine the distance and the direction of the signal source by trangulation manner. In the actual system, the multiple microphones array are set up around the ffield to identify the many location of the buzzer on the micro robots.



Fig.26 Array of high performance microphone(Sony ECM-G5M) with high directionality are employed around the field to measure the sound signal from the micro robots near the survivors

In the actual experiments, several high performance microphone with high directionality in Fig .26(Sony ECM-G5M)are employed around the field . In Fig.27 and Fig.28, the date acquisition/processing sequence and the data analyzing interface on PC were dipicted. Here the multiple sound signals can be processed quickly and show the location of the target point on the screen of PC.

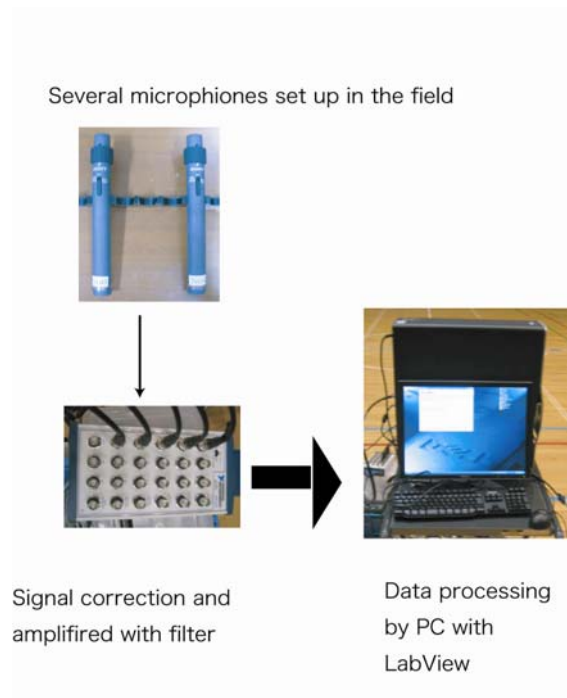


Fig.27 Block diagram of the date acquisition and processing sequence to determine the location of the signal sources.

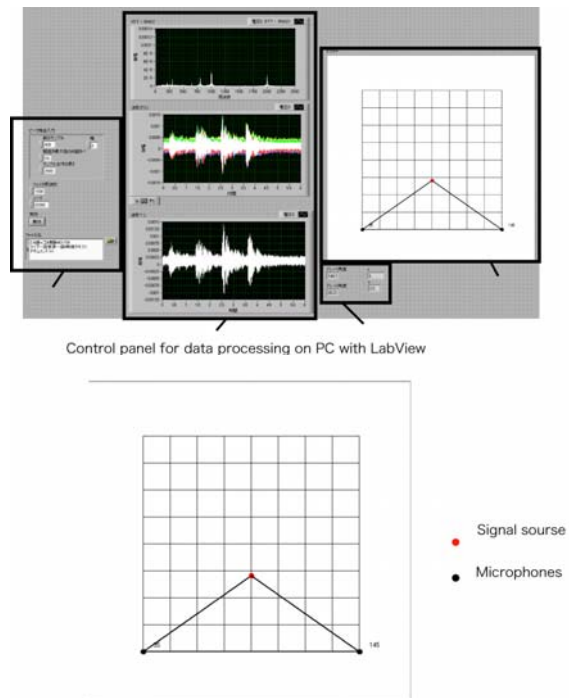


Fig.28 Graphic interface on the PC screen to manage the sound signal processing and the coordination map of the robots

The experinemtal set up is shown in Fig.29 although the actual situation might be more complicated with many walls and obstacles. Here several micro robots with the buzzer are distributed over the field and the sound signals come up sequentially to identify each location. Several experiments were carried out to check the repeatability and the accuracy.

In Fig.30, several typical results are shown with the map, here it is confirmed that the measured coordinate position have the deviation from the original position, because the sound reflection from the floor is not neglectible and the sound speed is so sensitive to the temperature of the air. However the error of these experiments are relatively small rather than the working range and 1 or 2 m error might be no problem to find out the survivors by the another visual instrument.



Fig.29 Experimental setup in basketball field to check the sound based location measuring system with the microphones array.

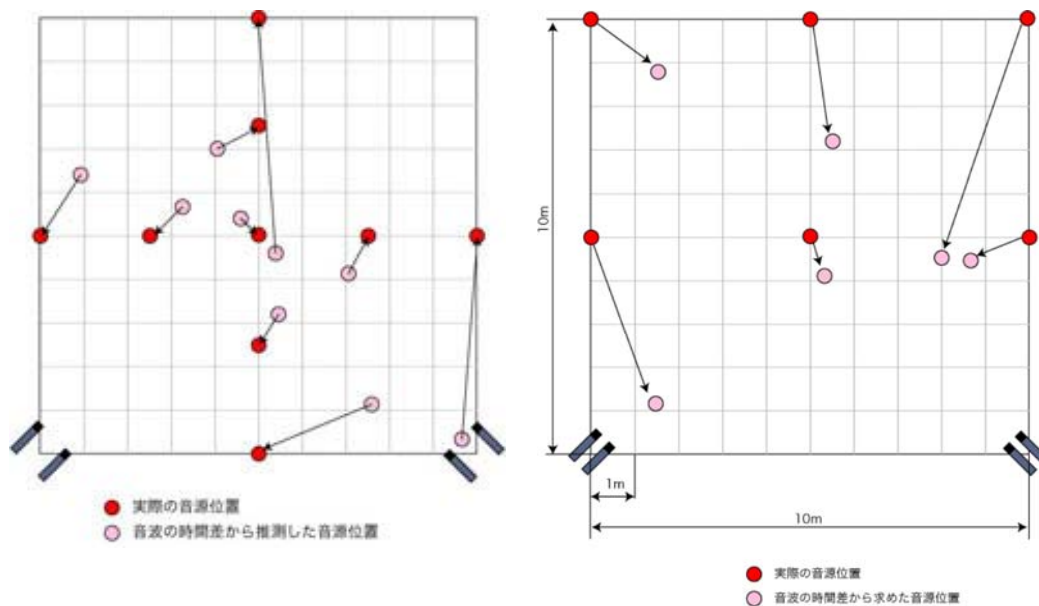


Fig.30 Typical experimental results to show the accuracy and the repeatability of the sound based coordinate measuring system for the distributed micro robots.

Overall experiment that includes the small robot can be launched from the mother-ship, they can self-navigate to approach the survivors and they can generate the sound alarm to indicate the location were carried out. Then the sound source measuring system can work to find out their locations as shown in Fig.31. Here the small robots succeeded in moving over the obstacles from the mother-ship by the launching mechanism and in keeping to moving to the signal source and then they can activate the buzzer sound to be identified its location by the sound source position scanning system.

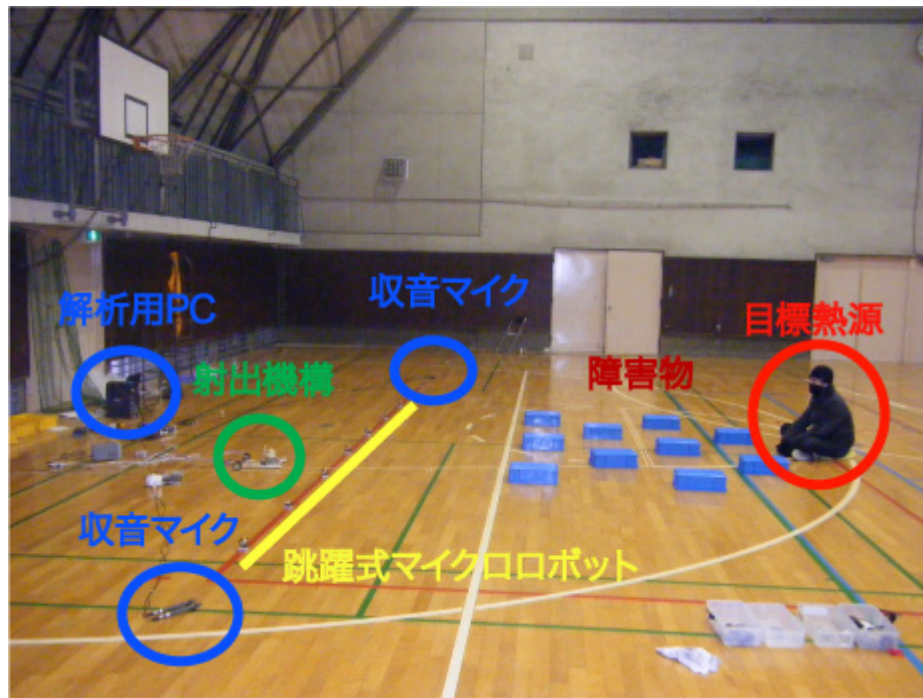


Fig.31 Overall experiment including the small robot can be launched from the mother-ship, they can self-navigate to approach the survivors and they can generate the sound alarm to indicate the location

5. Conclusion

In this report, it was proposed that many micro hopping robots would be effective for employment in the detection of trapped survivors under a rubble pile with the cooperation of larger rescue robots and rescue dogs. By virtue of the fact that access to survivors trapped in collapsed buildings is extremely difficult to accomplish (due to the small size of access holes) micro robots should become an integral part of any robo-rescue operation. Inexpensive micro robots can be manufactured for this purpose and by utilizing numerous micro robots (100s to 1000s) the deficiencies associated with the lower quality of the micro robots (relative to larger rescue robots) can be overcome by the advantages of higher quantity which will be permitted due to the lower cost of the micro robots. To quote a Russian proverb, "Quantity has a Quality all of its' own".

For the first stage of this research, a micro hopping locomotion mechanism, that is excited by a flat micro eccentric DC motor, was designed and developed. This locomotion mechanism functions without any wheels or legs and can move based upon the asymmetrical thrusting and lifting forces allowed by the design. After measuring the basic mobility characteristics of the micro hopping robot, for the second phase of this research an IR sensory element and control electronics were integrated onto the micro robot platform to allow the micro robot to approach a target signature (such as the thermal signal of a human subject). In a field experiment, these micro robots succeeded in tracking and maneuvering to a human target via a simple reactive control sequence and transmit the image information. Then these small robots can generate the sound alarm to be identified by the multiple microphone array. As the results of this process, the locations of small robots near the survivors can be identified and another big robots can be encouraged to remove the rubbles easily.

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